Scand J Work Environ Health 2006;32(4):276–284

# Occupational exposure to ionizing radiation and electromagnetic fields in relation to the risk of thyroid cancer in Sweden

*by Virginia Lope, BSc,[1] Beatriz Pérez-Gómez, MD,[1] Nuria Aragonés, PhD,[1] Gonzalo López-Abente, PhD,[1] Per Gustavsson, PhD,[2, 3] Birgitta Floderus, PhD,[4, 5] Mustafa Dosemeci, PhD,[6] Agustín Silva, PhD,[7] Marina Pollán, PhD[1]*

Lope V, Pérez-Gómez B, Aragonés N, López-Abente G, Gustavsson P, Floderus B, Dosemeci M, Silva A, Pollán M. Occupational exposure to ionizing radiation and electromagnetic fields in relation to the risk of thyroid cancer in Sweden. *Scand J Work Environ Health* 2006;32(4):276–284.

**Objectives** This study sought to ascertain the risk of thyroid cancer in relation to occupational exposure to ionizing radiation and extremely low-frequency magnetic fields (ELFMF) in a cohort representative of Sweden's gainfully employed population.
**Methods** A historical cohort of 2 992 166 gainfully employed Swedish male and female workers was followed up from 1971 through 1989. Exposure to ELFMF and ionizing radiation was assessed using three job exposure matrices based on industrial branch or occupational codes. Relative risks (RR) for male and female workers, adjusted for age and geographic area, were computed using log-linear Poisson models.
**Results** Occupational ELFMF exposure showed no effect on the risk of thyroid cancer in the study. However, female workers exposed to high intensities of ionizing radiation registered a marked excess risk (RR 1.85, 95% confidence interval (95% CI) 1.02–3.35]. This trend was not in evidence among the men.
**Conclusions** While the study confirms the etiologic role of ionizing radiation, with a higher incidence of thyroid cancer being recorded for the most-exposed female workers, our results do not support the possibility of occupational exposure to ELFMF being a risk factor for the development of thyroid cancer.

**Key terms** cohort; occupation; risk; thyroid neoplasm.

Thyroid cancer is an endocrine tumor with a low, yet growing, incidence, which is approximately threefold higher among women. Although the best-known risk factor is exposure to ionizing radiation, there are studies that link this tumor to a history of benign thyroid diseases or to dietary, hormonal, reproductive, and genetic factors (1).

There is sufficient evidence of the carcinogenicity of X and Gamma rays in humans (2). Such radiation is capable of damaging deoxyribonucleic acid (DNA), whether by direct action or by the creation of free radicals (3). The thyroid gland, particularly in children, is extremely vulnerable to these types of radiation, which can induce carcinomas, mainly of a papillary nature (1, 4, 5). The association between ionizing radiation and thyroid cancer has been reported in studies based on both external radiation (linked to medical irradiation or environmental exposures resulting from nuclear accidents or tests) and internal radiation (due either to the ingestion of radioisotopes for the purposes of therapy or diagnosis using radioactive iodine or to ingestion or inhalation of these particles as a consequence of their presence in the environment) (6).

While there is no conclusive evidence of extremely low-frequency magnetic fields (ELFMF) being carcinogenic (7), there is limited evidence of an association

1 Cancer and Environmental Epidemiology Section, National Center for Epidemiology, Carlos III Institute of Health, Madrid, Spain.
2 Department of Occupational and Environmental Health, Stockholm County Council, Sweden.
3 Division of Occupational Health, Department of Public Health Sciences, Karolinska Institutet, Stockholm, Sweden.
4 Department of Public Health Sciences, Karolinska Institutet, Stockholm, Sweden.
5 National Institute for Working Life, Stockholm, Sweden.
6 Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, Maryland, United States.
7 Department of Health and Medical-Social Sciences, Faculty of Medicine, Alcalá University, Madrid, Spain.

Reprint requests to: Ms V Lope, Cancer and Environmental Epidemiology Section, National Center for Epidemiology, Carlos III Institute of Health, C/Sinesio Delgado, 6, ES-28029 Madrid, Spain. [E-mail: vicarvajal@isciii.es]

between ELFMF and leukemia in children (3, 7, 8), which led the International Agency for Research on Cancer (IARC) to classify such radiation as "possibly carcinogenic to humans" (9). Insofar as thyroid cancer is concerned, some experimental studies with rodents have shown morphofunctional alterations to the thyroid after exposure to low-frequency electromagnetic fields (10–12), although, as yet, there has been no confirmation that such radiation might affect this gland in humans.

In occupational thyroid cancer studies, the best-documented high-risk occupations in the literature are those involving work with X rays (eg, health care physicians and dentists) (13–16). Nevertheless, some studies have failed to find a relationship between this tumor and occupational exposure to radiation (17–19).

In a recent study (20), our group analyzed the risks associated with different categories of professionals in a retrospective cohort comprising the economically active Swedish population. Among the results, there was evidence of excess risk among female medical technicians, who could be exposed to X rays, and an increased risk among fitters and wiremen in the electric installation industry, which might suggest the influence of ELFMF as a possible risk factor. With the aim of carrying out an in-depth analysis, we decided to use matrices of occupational exposure to ionizing radiation and ELFMF in order to quantify the possible effect associated with exposure to such agents.

Accordingly, this study sought to investigate the possible association between thyroid cancer and occupational exposure to ionizing radiation and ELFMF in the cohort. An earlier study based on the same Swedish population had also analyzed the relationship between ELFMF and thyroid cancer within a broader context aimed at linking occupation to all types of cancer (18). However, its follow-up period was shorter and, in the case of the women, it applied a job-exposure matrix designed for men; the matrix contained only the occupations most frequently found among the gainfully employed male population, something that might well entail misclassification problems (21). Our paper therefore reassessed this relationship, taking advantage of the recent publication of an ELFMF matrix designed for Swedish women (21) to use specific tools for each gender.

## Study population and methods

The base population for this historical cohort comprised all Swedish men and women who were gainfully employed at the time of the 1970 census, had also been recorded in the 1960 census, and were still alive and over the age of 24 years as of 1 January 1971. This base population encompassed 1 890 497 men and 1 101 669 women followed for 19 years until the end of 1989, plus a subcohort including only those who reported the same occupation in both the 1960 and 1970 censuses, comprising 755 728 men and 245 921 women.

Information was drawn from two combined data sets. The first source of data was the Swedish Cancer–Environment Register, covering all cancer cases and including information on occupation, industrial branch, residence, and different demographic variables from the 1960 and 1970 censuses (22, 23). This register was used to compute specific rate numerators. Thyroid cancer is classified as code 194 under the International Classification of Diseases (7th revision). Based on histological classification (24), lymphomas and sarcomas were excluded. The second data source comprised all persons in the 1970 census with information on occupation, industrial branch, residence in 1970, and, where applicable, date of death; this register was used to calculate specific rate denominators.

In the 1970 census, occupations were coded according to the Nordic Classification of Occupations (22). Similar codes were used in the 1960 census, and translations were made to the 1970 code when necessary. Occupations are represented by three-digit numbers. The first digit refers to one of ten major occupational sectors (0–9), where higher numbers indicate manual occupations and lower figures refer to occupations requiring longer education associated with a higher socioeconomic status. Finally, industrial branch was coded on a four-digit basis, in accordance with the Nordic Registry of Industries (25).

The overall person-time that each person contributed to the study was allocated to the corresponding cells of the variables of stratification. These variables were occupation, industrial branch, gender, 5-year age group (from 25–29 to 75–79 years), calendar time period (1971–1975, 1976–1980, 1981–1985, and 1986–1989), and county of residence in 1970.

Exposure to ELFMF and ionizing radiation was assessed by linking occupations to job-exposure matrices. For ELFMF, two job-exposure matrices, one for each gender, were available. The job-exposure matrix for men (26) covered the 100 most common occupations among men according to the 1990 Swedish census, the year in which the measures were taken. In addition, 10 comparatively rare occupations with estimates based on fewer than four measurements, but with definitely high exposures, were added [occupations according to table 10 of Floderus et al (26)]. Exposure levels in each occupation were estimated on the basis of full-shift measurements of at least four different workers, ensuring that altogether more than 1000 workers were studied. This matrix covered 85% of the men in the cohort and 88% in the subcohort. The matrix for the women (21), drawn up in 2001–2002, was designed to include at least 80% of the women gainfully employed in Stockholm County as per the 1980 census. A total of 471 measurements were performed in 49 occupations, with 5–24 measurements in each. This matrix covered 70% of the women in the cohort and 77% in the subcohort. In this study, two different measures of ELFMF exposure were used, namely, the arithmetic mean of the individual arithmetic mean workday values within any given occupation, using four exposure groups defined by cut-off points at 0.15, 0.25, and 0.35 µT, the lowest group being used as reference, and, to explore potential differences between intermittent and more continuous exposure, the percentage of the workday experiencing field magnitudes of over 0.20 µT, with three intervals (ie, <25%, 25%–50%, and >50%). These analyses were then repeated for the subcohort that reported the same occupation in the 1960 and 1970 censuses. Being a more specifically exposed group, this subcohort was mainly used to check the consistency of the results found in the general cohort.

In the case of ionizing radiation, a common occupation–industry exposure matrix for both genders, covering all persons in the cohort, was developed using the standard approach for developing generic job-exposure matrices (27). Briefly, each occupation and industry was classified according to intensity (none = 0, low = 1, medium = 2, high = 3) and probability of exposure (none = 0, low = 1, medium = 2, high = 3). The intensity estimates were based on information obtained from industrial hygiene and occupational health textbooks, computerized exposure databases, unpublished industrial hygiene reports, and personal experience. The probability index was based on the proportion of exposed workers within a given job or industry. Occupational and industrial exposure scores were also combined using the following algorithms for each person in the cohort: in cases in which exposure was dependent on occupation alone, the intensity and probability scores were calculated as the square of the occupational score, but, in cases in which exposure depended on both occupation and industry, the respective probability and intensity scores were computed by multiplying the score allocated to the occupation code by that allocated to the industry code. The final scores thus obtained were classified into four levels (none = 0, low = 1–2, medium = 3–4, high = 6–9). This matrix was solely applied to the main cohort, since the subcohort lacked information on the industry code in 1960, a time when a different classification was in use.

On the assumption that the observed number of cases was distributed in each stratum as a Poisson variable, log-linear Poisson models were fitted, including either ELFMF exposure groups or ionizing radiation categories of exposure, and duly adjusting for geographic risk area. In these models, the number of expected cases was introduced as an offset (28). As the expected number was computed on the basis of the age- and period-specific reference rates, the relative risk was likewise age- and period-adjusted. So that whether the effect was similar among different socioeconomic groups could be assessed, relative risks were additionally computed separately, taking into consideration the following three categories of workers: blue-collar workers, white-collar workers, and workers in the service sector.

In the case of ELFMF, an exposure–response trend was tested using the ELFMF exposure estimates as a continuous variable. In the case of ionizing radiation, it should be pointed out that the reference group for the combined intensity–probability score included both low-exposure intensity and unexposed categories.

## Results

Across the follow-up, 1103 and 1496 cases of thyroid cancer were diagnosed among the men and women, respectively. Tables 1 and 2 show the relative risks of this type of tumor among the men and women with respect

**Table 1.** Thyroid cancer risk among the men according to exposure to extremely low-frequency magnetic fields. (RR = relative risk, 95% CI = 95% confidence interval)

| Type of measure | Whole cohort | | | | | Subcohort 1960–1970 [a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Observed cases | Expected cases | RR [b] | 95% CI | P-value [c] | Observed cases | Expected cases | RR [b] | 95% CI | P-value [c] |
| Arithmetic mean of the means | | | | | | | | | | |
| ≤0.15 µT | 149 | 161.3 | 1.00 | · | | 70 | 71.7 | 1.00 | · | |
| 0.15–0.25 µT | 356 | 337.4 | 1.14 | 0.94–1.38 | | 156 | 143.4 | 1.11 | 0.84–1.48 | |
| 0.25–0.35 µT | 284 | 278.3 | 1.09 | 0.90–1.33 | | 155 | 153.4 | 1.03 | 0.77–1.36 | |
| >0.35 µT | 155 | 159.3 | 1.06 | 0.85–1.33 | 0.260 | 68 | 72.3 | 0.98 | 0.70–1.36 | 0.152 |
| Percentage of the time of exposure to >0.20 µT | | | | | | | | | | |
| ≤25% | 523 | 517.9 | 1.00 | · | | 266 | 261.5 | 1.00 | · | |
| 25–50% | 377 | 372.5 | 1.00 | 0.88–1.14 | | 160 | 155.6 | 1.01 | 0.83–1.23 | |
| >50% | 31 | 30.0 | 1.03 | 0.71–1.48 | 0.438 | 14 | 14.9 | 0.92 | 0.54–1.58 | 0.786 |

[a] Workers reporting the same occupation in the 1960 and 1970 censuses.
[b] Adjusted for age and geographic area.
[c] Trend test.

**Table 2.** Thyroid cancer risk among the women according to exposure to extremely low-frequency magnetic fields. (RR = relative risk, 95% CI = 95% confidence interval)

| Type of measure | Whole cohort | | | | | Subcohort 1960–1970 [a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Observed cases | Expected cases | RR [b] | 95% CI | P-value [c] | Observed cases | Expected cases | RR [b] | 95% CI | P-value [c] |
| Arithmetic mean of the means | | | | | | | | | | |
| ≤0.15 µT | 368 | 358.6 | 1.00 | · | | 86 | 88.9 | 1.00 | · | |
| 0.15–0.25 µT | 492 | 489.5 | 0.98 | 0.86–1.12 | | 118 | 129.7 | 0.94 | 0.71–1.24 | |
| 0.25–0.35 µT | 165 | 162.0 | 0.99 | 0.83–1.19 | | 36 | 37.4 | 1.00 | 0.68–1.47 | |
| >0.35 µT | 23 | 35.4 | 0.64 | 0.42–0.97 | 0.079 | 5 | 7.8 | 0.67 | 0.27–1.65 | 0.717 |
| Percentage of the time of exposure to >0.20 µT | | | | | | | | | | |
| ≤25% | 613 | 600.9 | 1.00 | · | | 133 | 140.8 | 1.00 | · | |
| 25–50% | 350 | 337.2 | 1.02 | 0.89–1.16 | | 84 | 92.2 | 0.97 | 0.74–1.27 | |
| >50% | 85 | 107.4 | 0.78 | 0.62–0.98 | 0.137 | 28 | 30.9 | 0.97 | 0.64–1.45 | 0.637 |

[a] Workers reporting the same occupation in the 1960 and 1970 censuses.
[b] Adjusted for age and geographic area.
[c] Trend test.

**Table 3.** Thyroid cancer risk among the men and women according to the intensity and probability of exposure to ionizing radiation. (RR = relative risk, 95% CI = 95% confidence interval)

| Type of measure | Men | | | | Women | | | |
|---|---|---|---|---|---|---|---|---|
| | Observed cases | Expected cases | RR [a] | 95% CI | Observed cases | Expected cases | RR [a] | 95% CI |
| Intensity | | | | | | | | |
| Unexposed | 1059 | 1047.55 | 1.00 | · | 1334 | 1344.71 | 1.00 | · |
| All potentially exposed | 23 | 28.78 | 0.79 | 0.52–1.20 | 28 | 25.03 | 1.13 | 0.78–1.65 |
| Low | – | 2.76 | 0.00 | 0.00– | – | 0.08 | 0.00 | 0.00– |
| Medium | 23 | 23.83 | 0.96 | 0.63–1.45 | 17 | 18.95 | 0.91 | 0.56–1.47 |
| High | – | 2.19 | · | · | 11 | 6.00 | 1.85 | 1.02–3.35 |
| Probability | | | | | | | | |
| Unexposed | 1059 | 1047.55 | 1.00 | · | 1334 | 1344.71 | 1.00 | · |
| All potentially exposed | 23 | 28.78 | 0.79 | 0.52–1.20 | 28 | 25.03 | 1.13 | 0.78–1.65 |
| Low | 11 | 13.19 | 0.82 | 0.46–1.49 | 6 | 9.03 | 0.67 | 0.30–1.50 |
| Medium | 12 | 14.01 | 0.85 | 0.48–1.50 | 5 | 2.78 | 1.83 | 0.76–4.40 |
| High | – | 1.57 | · | · | 17 | 13.22 | 1.30 | 0.80–2.10 |
| Combination of intensity & probability | | | | | | | | |
| None exposed + low intensity | 1059 | 1050.31 | 1.00 | · | 1334 | 1344.80 | 1.00 | · |
| Medium & high intensity | 23 | 26.02 | 0.88 | 0.58–1.33 | 28 | 24.95 | 1.14 | 0.78–1.65 |
| Medium intensity – low probability | 11 | 9.81 | 1.11 | 0.61–2.01 | 6 | 8.91 | 0.68 | 0.31–1.52 |
| Medium intensity – medium / high probability | 12 | 14.01 | 0.85 | 0.48–1.51 | 11 | 10.04 | 1.11 | 0.61–2.01 |
| High intensity – low probability | – | 0.62 | · | · | – | 0.04 | · | · |
| High intensity – medium / high probability | – | 1.57 | · | · | 11 | 5.96 | 1.86 | 1.03–3.37 |

[a] Adjusted for age and geographic area.

to the occupational exposure to ELFMF. Information on exposure to electromagnetic fields was available for 85% of the male workers and 70% of the female workers. Among the men, no association was observed with either magnitude or time of exposure, but there was a slight downward trend in the response to increased levels of exposure. Among the women, in contrast, exposure to levels exceeding 0.35 µT and exposure to doses exceeding 0.20 µT for more than half the workday seem to have had a protective effect vis-à-vis thyroid cancer. The analysis of the subcohort revealed a similar trend, although the estimates were less precise due to the lower number of women. Appendix 1 shows the occupations and industries included in the high-intensity category, together with the number of observed and expected cases among both genders.

Table 3 shows the relative risks of thyroid cancer for the men and women in accordance with the intensity and probability of occupational exposure to ionizing radiation. While no trend in the risk of this tumor was observed for the men, the women employed in jobs with a high intensity of exposure registered an excess risk of 85%. In addition, high relative risks were found for the women employed in jobs with a medium–high probability of occupational exposure, although a clear trend could not be observed. When both dimensions were combined, the women employed in jobs with a high intensity and medium–high probability of exposure again registered an excess risk of 86%. A more-detailed analysis by occupation (see occupations included in the highest exposure categories in appendix 2) showed that the high risk observed in this category of exposure was exclusively attributable to female X-ray assistants or medical laboratory technicians.

Finally, no differences in the relative risks were found when these analyses were performed separately for the white-collar workers, blue-collar workers, and workers in the service sector (data not shown).

## Discussion

The aim of this cohort study targeting the Swedish economically active population was to estimate, using job-exposure matrices, the risk of thyroid cancer in association with occupational exposure to ELFMF and ionizing radiation. The results indicate that ELFMF do not increase the incidence of this type of tumor. A raised risk was observed among the women exposed to high intensities of ionizing radiation in their workplace.

Our study suffers from some limitations that call for an explanation. First, it was impossible to distinguish between the different histological types of thyroid cancer. It would have been interesting to ascertain what proportion of cases corresponded to papillary carcinoma; this tumor is of the type that has been most frequently associated with exposure to ionizing radiation, and its incidence appears to have risen notably in Sweden in the last 50 years, a phenomenon that has been attributed to the widespread use of radiotherapy for treating benign diseases of the neck, although other hypotheses cannot be ruled out (29).

Second, the use of job exposure matrices is an imperfect measure for estimating exposure, and it generally implies nondifferential classification bias. The importance of this problem depends on the variability of exposure within the considered occupational groups and possible changes in exposure across time. This misclassification, coupled with the impossibility of measuring exposure outside the job setting, would inevitably entail an underestimation of the effect. In the case of ELMF, it must be borne in mind, moreover, that the matrices were constructed on the basis of measurements taken after the commencement of the follow-up. Yet we feel that, even with these limitations, job-exposure matrices constitute an efficient method for complementing the analysis of each of the occupations of interest because, when people with different occupations having a similar range of estimated exposure are pooled, such matrices provide increased power. Finally, workers were classified according to their occupation in the 1970 census, and job changes during the follow-up were not considered.

Three matrices based on different methodologies were used in this study. The job-exposure matrices used to evaluate occupational exposure to ELFMF among the men and women separately were developed in Sweden (21, 26). Of the 49 occupations present in Forssen's matrix for women, 29 are also featured in Floderus' matrix, purpose-designed for men. In general, there was good concordance between most of the common occupations. There were some exceptions, however, owing possibly to the different activities performed by the two genders and to the different time frame in which the studies were undertaken: whereas Floderus' ELFMF exposure measurements were taken from 1989 through 1991, those of Forssen were measured over the period 2001–2002 (21). Insofar as the job-exposure matrix for ionizing radiation is concerned, it is a qualitative matrix and potentially represents the occupational ionizing radiation exposure for the study period.

Last, another limitation of the present study lies in the impossibility of adjusting for factors other than age, period, and geographic area. However, as explained in the Introduction section, the principal known etiologic factor of thyroid cancer is precisely exposure to ionizing radiation.

In our study, no association between occupational exposure to ELFMF and the risk of thyroid cancer was observed among the men. This same absence of effect was also seen in other earlier studies (18, 30). Yet there are suggestions to show that the pituitary gland is susceptible to being impaired by ELFMF exposure; therefore, hormone-dependent organs could be affected by such exposure (31, 32). Indeed, it has been suggested that functional changes induced in the endocrine system by exposure to low-frequency electromagnetic fields could conform to a nonlinear dose-response relationship (33). Opposition to this theory comes from Selmaoui et al (34), who reported that, under experimental conditions, acute exposure to ELFMF did not affect the hormones of the hypothalamic-pituitary-thyroid axis in young persons.

For the women, in contrast, our results indicate a lower risk in association with high levels of ELFMF exposure or prolonged ELFMF exposures over time. The only occupations in which the women were exposed to relatively high levels (above 0.35 μT) for more than half their workday were "cashiers in retail stores & restaurants" and "cooks". In a case–control study conducted in Canada, Deadman et al considered that, of the jobs commonly performed by women, both occupations ranked among those having the greatest exposure to ELFMF (35). This unexpected result is difficult to interpret. We have been unable to find data in the literature that would justify a protective effect for these radiations, and are therefore inclined to view this risk deficit as a chance finding.

The relationship between ionizing radiation and thyroid cancer has been known for decades; yet the risk associated with occupational exposure to such radiation has proved more controversial. Whereas some published studies report finding no association (17, 19), others report an excess risk for certain occupations, essentially those requiring contact with X rays (13, 15, 16, 36–40). In our matrix, the only occupation with high intensity and medium–high probability of exposure was "X-ray assistants, medical laboratory technicians". We observed no association for the men, although it has to be said that few men are exposed to high intensities, as is shown by the low number of expected cases in the highest exposure category. The intensity and probability of exposure was measured using the same job-exposure matrix for both genders, and it was based on expert judgment. If anything, one would have expected the matrix to work better among the men than among the women and that there would be a greater degree of misclassification among the female workers. It is interesting to note that the effect was observed solely for the women. No data were available regarding gender-based differences in levels of exposure with respect to health-related professions that could explain this result. On the other hand, gender-related differences in susceptibility cannot be ruled out. In fact, women have been described as being more sensitive to radiation-induced thyroid cancer than men (5). Ron et al (4) also reported a greater excess relative risk of thyroid cancer among women versus men, but the results were not consistent. A plausible explanation would be based on hormonal and reproductive factors in that high concentrations of thyroid stimulating hormone (TSH) are associated with the risk of this tumor and the TSH secretion rate rises during pregnancy, birth, and the use of oral contraceptives (1, 16). The greater risk of thyroid cancer among women was observed for the high-intensity exposure category. This result is consistent with the few studies available that have suggested that, at low or moderate doses, the dose–response relationship could be modeled as a linear relationship (4, 5). Among women, the greatest occupational exposure to ionizing radiation is found in the medical sector (41). The only women exposed to such a high level of intensity in our cohort were X-ray assistants and medical laboratory technicians. In a study based on the same Swedish registry—albeit in an earlier period—Carstensen et al (13) also observed a high occupational risk of thyroid cancer among X-ray operators and laboratory assistants. Likewise, Wang et al (42), in a population-based cohort of Chinese medical X-ray workers, observed a possible excess of thyroid cancer linked to occupational exposure to ionizing radiation. Some studies in the United States have reported the same result among radiologists (39, 40, 43).

Workers exposed to medium intensity and a medium to high probability of ionizing radiation corresponded to dental- and health-related occupations. It should be noted here that, in Sweden, regular dental examinations begin at a very tender age and the number of dental radiographs per person a year is considerably high (16). This, in turn, means a greater possibility of occupational exposure of the thyroid to high cumulative doses of ionizing radiation among dental professionals; this possibility may explain the high risk of papillary carcinoma that other authors have reported among these workers in Sweden (16, 37). However, in our study, the number of observed and expected cases was very similar.

Our results indicate that, despite the existing radiological protection regulations, a degree of excess risk is in evidence in certain health occupations. The guidelines drawn up by the International Commission on Radiological Protection (ICRP), founded in 1928, have constituted a solid basis for establishing regulations in the respective countries. The first quantitative maximum permitted doses were issued in 1934 and remained in force until 1950 (44). The European Community laid down the basic regulations governing health protection against ionizing-radiation-induced risks in the 80/836/Euratom and 84/476/Euratom directives. In Sweden, the present Swedish Radiation Protection Institute's regulations are based on the Swedish Radiation Protection Ordinance (1988:293) (45), although the country has had rules in place addressing radiation protection since 1941.

In the first place, this study has allowed for an analysis of occupational exposure to ELFMF in a large cohort (N=2 992 166 persons) over a considerable follow-up period (19 years) through the use of two gender-specific job-exposure matrices, which, unlike in other studies, has enabled us to observe the heterogeneity of the job tasks performed by men and women. This same matrix has also made it possible for both the level and duration of exposure to ELFMF to be assessed and so to distinguish between intense and prolonged exposures. In the second place, this study has enabled us to analyze occupational exposure to ionizing radiation, thanks to a job-exposure matrix that evaluates, in terms of intensity and probability, exposure to the different occupations and industries existing in Sweden, thereby covering all workers in our cohort. Although there are Swedish studies that have previously studied the relationship between thyroid cancer and exposure to ELFMF (18) or ionizing radiation (13, 16, 37), they involved fewer persons and a shorter follow-up period.

In conclusion, our results confirm the absence of an ELFMF-related effect on the risk of thyroid cancer. Yet we did find evidence of an association with occupational exposure to ionizing radiation among women, with an excess risk being detected in health occupations, notwithstanding dosimetric control and radiological protection regulations. It would thus be of interest if additional epidemiologic studies could be conducted using individual dosimetry information on the aforementioned professions in order to test the adequacy of the exposure limits in relation to the risk of suffering thyroid cancer and to investigate the possible interactive effect of ionizing radiation with other carcinogens.

## Acknowledgments

This study was financed by the Carlos III Institute of Public Health (grant 03/0007 and EPY 1122/03) and by the Spanish Network for Cooperative Research in Epidemiology and Public Health (RCESP-FIS C03–09).

## References

1. Ron E. Thyroid Cancer. In: Schottenfeld F. Cancer epidemiology and prevention. 2d ed. New York (NY): Oxford University Press; 1996. p 1000–21.
2. International Agency for Research on Cancer (IARC). IARC working group on the evaluation of carcinogenic risks to humans: ionizing radiation, part I: X- and gamma- radiation and neutrons. Lyon (France): IARC; 1999. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans 2000;75, Pt 1, p 1–448.
3. Wakeford R. The cancer epidemiology of radiation. Oncogene. 2004;23(38):6404–28.
4. Ron E, Lubin JH, Shore RE, Mabuchi K, Modan B, Pottern LM, et al. Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies. Radiat Res. 1995;141(3): 259–77.
5. Shore RE. Issues and epidemiological evidence regarding radiation-induced thyroid cancer. Radiat Res. 1992;131(1):98–111.
6. Fraker D, Skarulis M, Livolsi V. Thyroid tumors. In: DeVita V, Hellman S, Rosenberg S. Cancer principles & practice of oncology. 6th ed. Philadelphia (PA): Lippincott Williams & Wilkins; 2001. p. 1740–63.
7. Report of an advisory Group on Non-ionising Radiation. ELF Electromagnetic Fields and the Risk of Cancer. Chilton (United Kingdom): National Radiological Protection Board: 2001. Documents of the NRPB, vol 12, no 1. [See http://www.hpa.org.uk/radiation/publications/documents_of_nrpb/pdfs/doc_12_1.pdf]
8. Ahlbom IC, Cardis E, Green A, Linet M, Savitz D, Swerdlow A. Review of the epidemiologic literature on EMF and Health. Environ Health Perspect. 2001;109 suppl 6:911–33.
9. International Agency for Research on Cancer (IARC). Non-ionizing radiation, part 1: static and extremely low-frequency (ELF) electric and magnetic fields. Lyon (France): IARC; 2002. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, 80 p. 1–395.
10. Rajkovic V, Matavulj M, Lukac T, Gledic D, Babic L, Lazetic B. Morphophysiological status of rat thyroid gland after subchronic exposure to low frequency electromagnetic field. Med Pregl. 2001;54(3–4):119–27.
11. Rajkovic V, Matavulj M, Gledic D, Lazetic B. Evaluation of rat thyroid gland morphophysiological status after three months exposure to 50 Hz electromagnetic field. Tissue Cell. 2003;35(3):223–31.
12. Wright NA, Borland RG, Cookson JH, Coward RF, Davies JA, Nicholson AN, et al. Biological studies with continuous-wave radiofrequency (28 MHz) radiation. Radiat Res. 1984;97(3):468–77.
13. Carstensen JM, Wingren G, Hatschek T, Fredriksson M, Noorlind-Brage H, Axelson O. Occupational risks of thyroid cancer: data from the Swedish Cancer-Environment Register, 1961–1979. Am J Ind Med. 1990;18(5):535–40.
14. Sont WN, Zielinski JM, Ashmore JP, Jiang H, Krewski D, Fair ME, et al. First analysis of cancer incidence and occupational radiation exposure based on the National Dose Registry of Canada. Am J Epidemiol. 2001;153(4):309–18.
15. Wang JX, Boice JD Jr, Li BX, Zhang JY, Fraumeni JF Jr. Cancer among medical diagnostic x-ray workers in China. J Natl Cancer Inst. 1988;80(5):344–50.
16. Wingren G, Hallquist A, Hardell L. Diagnostic X-ray exposure and female papillary thyroid cancer: a pooled analysis of two Swedish studies. Eur J Cancer Prev. 1997;6(6):550–6.
17. Fincham SM, Ugnat AM, Hill GB, Kreiger N, Mao Y. Is occupation a risk factor for thyroid cancer? J Occup Environ Med. 2000;42(3):318–22.
18. Floderus B, Stenlund C, Persson T. Occupational magnetic field exposure and site-specific cancer incidence: a Swedish cohort study. Cancer Causes Control. 1999;10(5):323–32.
19. Ron E, Kleinerman RA, Boice JD Jr, LiVolsi VA, Flannery JT, Fraumeni JF Jr. A population-based case-control study of thyroid cancer. J Natl Cancer Inst. 1987;79(1):1–12.
20. Lope V, Pollan M, Gustavsson P, Plato N, Perez-Gomez B, Aragones N, et al. Occupation and thyroid cancer risk in Sweden. J Occup Environ Med. 2005;47(9):948–57.
21. Forssen UM, Mezei G, Nise G, Feychting M. Occupational magnetic field exposure among women in Stockholm County, Sweden. Occup Environ Med. 2004;61(7):594–602.
22. Cancer -Miljöregistret 1960–70. Stockholm: Center for epidemiology, Swedish National Board of Health and Welfare; 1994.
23. Barlow L, Eklund G. Ny datatbank öppen för forskare [Opening of a new database for research scientists. FoB 60 and 70 linked with the cancer registry]. Läkartidningen. 1995; 92(13):1344, 1347.
24. World Health Organization (WHO). Histology code. Geneva: WHO; 1957. WHO/HS/CANC/24.
25. Swedish Standard Industrial Classification of all Economic Activities. Stockholm: 1977. Second edition of the 1969 standard, Statistiska Centralbyran, Meddelanden I samordningsfragor, 9.
26. Floderus B, Persson T, Stenlund C. Magnetic-field exposures in the workplace: reference distribution and exposures in occupational groups. Int J Occup Environ Health. 1996; 2(3):226–38.
27. Dosemeci M, Cocco P, Gomez M, Stewart PA, Heineman EF. Effects of three features of a job-exposure matrix on risk estimates. Epidemiology. 1994;5(1):124–7.
28. Breslow NE, Day NE. Statistical methods in cancer research, volume II: the design and analysis of cohort studies. Lyon (France): IARC; 1987. IARC Scientific Publications 82, p. 1–406.
29. Lundgren CI, Hall P, Ekbom A, Frisell J, Zedenius J, Dickman

PW. Incidence and survival of Swedish patients with differentiated thyroid cancer. Int J Cancer. 2003;106(4):569–73.
30. Theriault G, Goldberg M, Miller AB, Armstrong B, Guenel P, Deadman J, et al. Cancer risks associated with occupational exposure to magnetic fields among electric utility workers in Ontario and Quebec, Canada, and France: 1970–1989. Am J Epidemiol. 1994;139(6):550–72.
31. Floderus B, Tornqvist S, Stenlund C. Incidence of selected cancers in Swedish railway workers, 1961–79. Cancer Causes Control. 1994;5(2):189–94.
32. Hakansson N, Floderus B, Gustavsson P, Johansen C, Olsen JH. Cancer incidence and magnetic field exposure in industries using resistance welding in Sweden. Occup Environ Med. 2002;59(7):481–6.
33. Marino AA, Wolcott RM, Chervenak R, Jourd'heuil F, Nilsen E, Frilot C, et al. Coincident nonlinear changes in the endocrine and immune systems due to low-frequency magnetic fields. Neuroimmunomodulation. 2001;9(2):65–77.
34. Selmaoui B, Lambrozo J, Touitou Y. Endocrine functions in young men exposed for one night to a 50-Hz magnetic field: a circadian study of pituitary, thyroid and adrenocortical hormones. Life Sci. 1997;61(5):473–86.
35. Deadman JE, Infante-Rivard C. Individual estimation of exposures to extremely low frequency magnetic fields in jobs commonly held by women. Am J Epidemiol. 2002; 155(4):368–78.
36. Antonelli A, Silvano G, Gambuzza C, Bianchi F, Tana L, Baschieri L. Is occupationally induced exposure to radiation a risk factor of thyroid nodule formation?. Arch Environ Health. 1996;51(3):177–80.
37. Wingren G, Hallquist A, Degerman A, Hardell L. Occupation and female papillary cancer of the thyroid. J Occup Environ Med. 1995;37(3):294–7.
38. Hallquist A, Hardell L, Degerman A, Boquist L. Occupational exposures and thyroid cancer: results of a case-control study. Eur J Cancer Prev. 1993;2(4):345–9.
39. Boice JD Jr, Mandel JS, Doody MM, Yoder RC, McGowan R. A health survey of radiologic technologists. Cancer. 1992;69(2):586–98.
40. Sigurdson AJ, Doody MM, Rao RS, Freedman DM, Alexander BH, Hauptmann M, et al. Cancer incidence in the US radiologic technologists health study, 1983–1998. Cancer. 2003;97(12):3080–9.
41. Hunt VR. Occupational radiation exposure of women workers. Prev Med. 1978;7(3):294–310.
42. Wang JX, Zhang LA, Li BX, Zhao YC, Wang ZQ, Zhang JY, et al. Cancer incidence and risk estimation among medical x-ray workers in China, 1950–1995. Health Phys. 2002; 82(4):455–66.
43. Haselkorn T, Bernstein L, Preston-Martin S, Cozen W, Mack WJ. Descriptive epidemiology of thyroid cancer in Los Angeles County, 1972–1995. Cancer Causes Control. 2000; 11(2):163–70.
44. Taylor LS. History of the International Commission on Radiological Protection (ICRP). 1958. Health Phys. 2002; 82(6):789–94.
45. SSI's Regulations. Stockholm: The Swedish Radiation Protection Authority. [updated 2004 March; cited 2005 September 21]. Available from: http://www.ssi.se/forfattning/eng_forfattlista.html.

Received for publication: 22 November 2005

## Appendix 1

### Observed and expected cases of thyroid cancer for occupations classified into the highest categories of exposure to extremely low-frequency magnetic fields among the men and women

| Occupation | | Observed cases | Expected cases |
|---|---|---|---|
| Arithmetic mean of the means >0.35 μT | | | |
| Men | | | |
| 4 | Chemical engineers & technicians | 7 | 7.06 |
| 5 | Metallurgists & mining engineers & technicians | 2 | 3.82 |
| 332 | Shop managers | 11 | 8.68 |
| 404 | Horticultural managers & supervisors | – | 1.38 |
| 412 | Horticultural workers | 6 | 8.25 |
| 441 | Forest workers & log-drivers | 30 | 22.18 |
| 621 | Aircraft pilots, navigators & flight engineers | – | 0.53 |
| 631 | Railway engine drivers & assistants | 6 | 4.41 |
| 632 | Railway guards | 3 | 4.75 |
| 661 | Sorting clerks & postmen | 7 | 5.84 |
| 678 | Railway linesmen | – | 0.92 |
| 711 | Tailors & dressmakers | – | 1.35 |
| 716 | Industrial confectionists | – | 0.38 |
| 735 | Black smiths & forgers | 3 | 3.71 |
| 737 | Wire & tube drawers | – | 1.25 |
| 738 | Other metal processing work | 2 | 1.74 |
| 741 | Precision toolmakers | 3 | 3.06 |
| 742 | Watchmakers | – | 0.94 |
| 743 | Opticians | – | 0.51 |
| 753 | Sheet metal workers | 5 | 7.44 |
| 755 | Welder & flame cutters | 15 | 12.69 |
| 756 | Construction smiths | 2 | 3.98 |

(continued)

### Appendix 1 (continued)

| Occupation | | Observed cases | Expected cases |
|---|---|---|---|
| 761 | Electrical fitters & wiremen | 25 | 19.74 |
| 811 | Glass formers & cutters | – | 0.80 |
| 813 | Glass & ceramics kilnmen | – | 0.44 |
| 818 | Other glass, pottery & tile work | – | 0.37 |
| 828 | Other food processing work | – | 0.46 |
| 834 | Paper pulp workers | 7 | 3.56 |
| 871 | Stationary engine & related equipment operators | 5 | 4.09 |
| 875 | Truck & conveyor operators | 9 | 9.85 |
| 931 | Building caretakers | 7 | 15.13 |
| Women | | | |
| 204 | Cashiers in retail stores & restaurants | 10 | 18.51 |
| 912 | Cooks | 13 | 16.86 |
| >50% of time exposed to >0,35 μT | | | |
| Men | | | |
| 32 | Dentists | – | 2.23 |
| 87 | Composers & musicians | – | 1.26 |
| 301 | Working proprietors, wholesale trade | 2 | 3.13 |
| 302 | Working proprietor, retail trade | 18 | 14.68 |
| 309 | Nonspecified working proprietors | – | 0.01 |
| 332 | Shop managers | 11 | 8.68 |
| Women | | | |
| 44 | Dental hygienists | 6 | 7.26 |
| 204 | Cashiers in retail stores & restaurants | 10 | 18.51 |
| 302 | Working proprietors, retail trade | 9 | 14.11 |
| 651 | Post-office clerks | 10 | 12.70 |
| 912 | Cooks | 13 | 16.86 |
| 921 | Waiters & waitresses | 37 | 37.99 |

### Appendix 2

**Observed and expected cases of thyroid cancer for occupations and industries classified in the categories for high-intensity ionizing radiation among the men and women**

| Occupation | Industry | | Men | | Women | |
|---|---|---|---|---|---|---|
| | | | Observed cases | Expected cases | Observed cases | Expected cases |
| High intensity – Low probability | | | | | | |
| 504 Other mine and quarry workers | 101 | Iron ore mines | – | 0.55 | – | 0.04 |
| | 102 | Other ore mines | – | 0.07 | – | 0.00 |
| High intensity – Medium to high probability | | | | | | |
| 45 X-ray assistants, medical laboratory technicians | 15 | Veterinary medicine | – | 0.00 | – | 0.02 |
| | 260 | Pulp grinding plants | · | · | – | 0.00 |
| | 340 | Iron and steel plants | · | · | – | 0.00 |
| | 350 | Machine industry | · | · | – | 0.01 |
| | 363 | Automotive plants | · | · | – | 0.00 |
| | 618 | Other wholesale items and assortments | · | · | – | 0.00 |
| | 655 | Perfume and over-the-counter pharmaceutics | · | · | – | 0.00 |
| | 801 | Diplomacy and consular activity | · | · | – | 0.00 |
| | 803 | National defense | – | 0.00 | – | 0.00 |
| | 807 | Other state administration | – | 0.00 | – | 0.00 |
| | 811 | State secondary grammar schools, training | – | 0.00 | · | · |
| | 812 | Elementary and experimental schools | · | · | – | 0.00 |
| | 820 | Health care | – | 1.52 | 11 | 5.89 |
| | 830 | Research and scientific institutes | · | · | – | 0.00 |
| | 834 | Social work | – | 0.04 | – | 0.02 |
| | 837 | Other pertinent jobs | · | · | – | 0.00 |
| | 999 | Unspecific jobs | · | · | – | 0.00 |